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Richard W. Powell and Donald G. Eide

June 1974

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16. Abstract

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INVESTIGATION OF ABORT PROCEDURES FOR SPACE SHUTTLE-TYPE VEHICLES

Richard W. Powell and Donald G. Eide

Summary

An investigation has been made of abort procedures for space shuttle-type vehicles using a point mass trajectory optimization program known as POST. This study determined the minimum time gap between immediate and once-around safe return to the launch site from a baseline due-East launch trajectory for an alternate space shuttle concept which experiences an instantaneous loss of 25 percent of the total main engine thrust.

INTRODUCTION

A prime safety consideration in the design of any space vehicle for reuse is the ability of the vehicle to return intact to a designated landing site after a failure event. Ideally, this should be accomplished with a minimum impact on the nominal mission. A computer program has been developed that can determine abort capability along any ascent trajectory without the customary parametric, multirun approach. This program determines unsafe gaps in the trajectory, and can also be used to define the changes required to close any gaps. In this way, the minimum additional fuel, and hence, the smallest weight penalty for the requirement of continuous abort capability can be ascertained.

The program is a point mass trajectory optimization simulation which can calculate the maximum and minimum time into the nominal flight that a particular operational procedure would provide a safe return to the specified landing area. Its capability has been demonstrated through application to an alternate shuttle concept that experiences a 25 percent loss in main engine thrust while flying an ascent trajectory optimized for performance. The effectiveness of various operational modes in reducing unsafe abort gaps was analyzed for both immediate return to the launch site and for return after circumnavigating the earth.

SYMBOLS

AOA	Abort Once Around
ETR	Eastern Test Range
IRTLS	Immediate Return to Launch Site
I_{sp}	vacuum specific impulse, sec.
q	dynamic pressure (N/m^2)
OMS	Orbital Maneuvering System
SRB	Solid Rocket Booster
T/W	Thrust to Weight Ratio
α	angle of attack, deg.
σ	bank angle, deg. (first rotation about atmospheric relative velocity vector)
η	throttling coefficient

θ_i inertial pitch angle, deg.

θ_r relative pitch angle, deg.

ψ yaw angle relative to velocity vector, deg.

METHOD OF ANALYSIS

The recently developed Program to Optimize Shuttle Trajectories (POST), reference 1, provides simulation flexibility allowing the user to switch controls between inertial and relative coordinate systems during the trajectory. Combining this flexibility with an efficient targeting and optimization scheme permits rapid analysis of alternate abort procedures. Additional guidance flexibility, not provided in the basic simulation, has been incorporated into the program to allow modulation of angle of attack so that the vehicle would not exceed the specified normal acceleration and q-α constraints. The vehicle flew a pre-programed, statically trimmed, ascent trajectory until thrust degradation occurred. At that time, the abort procedures were initiated. Failure time was varied within the program to determine either maximum or minimum times that thrust could be lost and a safe return effected while meeting all inflight constraints. The program was applied to ascertain vehicle capability of performing both an immediate return to the launch site (IRTLS) and an abort once around (AOA) maneuver.

PROBLEM DESCRIPTION

An alternate space shuttle concept, shown in figure 1, was chosen for the investigation. It utilized four main engines (individual vacuum thrust of 1,600 kN) with two of the engines on the orbiter and the other two, which are retractable, thrusting along the external tank. The solid rocket boosters were of the 3.05 m diameter 7-segment class. Table 1 lists the main characteristics of the vehicle; aerodynamic data were selected from available wind-tunnel results (references 2, 3, and 4). The main orbiter engines provided all the thrust vector control for static trim during nominal ascent. The baseline mission was a due-East launch from ETR into a 92.6 x 185.2 km orbit with a 29,500 kg payload. The trajectory profile shown in figure 2, which had been optimized to provide maximum injected weight, maintained the vehicle in a "heads-down" attitude. The fuel in the external tank was depleted ≈14 seconds prior to orbit injection. At that time, the two engines located behind the tank were shut down and retracted into the orbiter as the tank was jettisoned; the flight then continued to orbit with two main engines using internal propellant. To reduce the velocity losses associated with reduced T/W after staging the SRBs, the OMS engines were used for ≈ 340 seconds.

For this analysis, the failure mode assumed was the loss of one main engine on the orbiter. Thus, during the abort, three main engines would be available until the tank, with the two retractable main engines, was jettisoned leaving only one orbiter main engine operational. In the abort mode, the two retractable engines were jettisoned with the tank. In addition, it was assumed that all load-related constraints could be increased 40 percent during the abort. The abort guidelines are summarized as follows:

1. No reaction time required to initiate the abort procedures.
2. No winds.
3. No heating constraints.
4. SRB thrust termination instantaneous.
5. Maximum allowable acceleration = 4.2 g's.
6. Maximum q = 43,570 N/m^2.
7. Maximum q-α = 187,690 N/m^2 deg.

DISCUSSION OF RESULTS

In the immediate return category, three different propulsion options were considered. The first assumed shutdown of all remaining engines upon failure of one orbiter engine; immediate separation of the SRBs and the external tank with the two retractable main engines; and an unpowered glide to the launch site. In the second option, the glide is supplemented by use of the OMS engines. A third option used all the operable propulsion retaining the SRBs until depleted and staging the tank at the optimum point.

In the once-around category, three different operational techniques were also investigated. In the first, the three remaining main engines with the OMS were used until the external propellant was depleted. At this time, the tank with the retractable main engines was jettisoned and thrust was continued with the OMS and one main engine using internal propellant. The second technique differed from the first in that the depleted tank is not jettisoned until all internal fuel is used. Crossfeed from the internal fuel to the retractable main engines was assumed, and thus, a higher thrust level was maintained until all fuel is depleted. The third technique differed from the first only in that during the thrust period, the vehicle was yawed. This yaw maneuver changed the inclination of the orbit and reduced the crossrange requirements for reentry.

Figures 3 through 11 show the trajectories for the limiting times under each of the conditions studied. The left-hand side of the figure presents the altitude-velocity profile and the right side shows the optimal control histories.

IRTLS - No Propulsion.- The first abort mode studied had the vehicle, at time of failure, instantaneously shut down all engines while simultaneously jettisoning the external tank with two main engines and SRBs. For the minimum time safe abort, the vehicle was rolled from its nominal "heads down" position, performed an aerodynamic turn, and glided back to the launch site. The velocity-altitude profile of figure 3 shows that the vehicle at $t = 23$ seconds reached an altitude of ≈2 km with a velocity of 170 m/sec, where intact abort could be initiated with power off. The vehicle coasted to an altitude of ≈3 km where its speed has decreased to 53 m/sec; during the following descent, the flight speed more than doubled. The trajectory terminated at an attitude of 0.7 km where the vehicle was considered to enter the landing phase. The vehicle's commanded attitude (angle of attack (α) and bank angle (σ)) are shown on the right-hand side of the figure. To reduce the initial flight path angle, the vehicle was pitched to a negative angle of attack before the initial roll signal. After this, α and σ commands became compromises between those for maximum glide range (α for $(L/D)_{max}$ and $\sigma = 0$) and those for maximum turning rate (α for $C_{L_{max}}$ and $\sigma = 90°$).

The maximum time to failure that can be safely handled by this mode is 68 seconds as shown in figure 4. At time of failure, the initial flight path angle was less than in the minimum-time case and the vehicle was initially rolled to the "heads up" position and pitched to a large α to reduce downrange distance. This pitchup was constrained by the q-α boundary. This constraint as well as the desire to reduce the accrued downrange determined α and σ commands throughout the remainder of the flight.

<u>IRTLS - OMS Propulsion Only</u>.- Augmenting the glide capability of the vehicle with the OMS, maximum $T/W = 0.16$, reduced the minimum time of failure for safe return by 0.5 seconds from the "no propulsion" case (compare figures 5 and 3.) The maximum time for safe return was increased by 7 seconds (figures 6 and 4). The initial maneuvers for both the minimum and maximum abort times were similar to the "no propulsion" mode; however, with OMS, the latter part of the maximum time trajectory required α-modulation to meet the q-α constraint.

<u>IRTLS - All Available Propulsion</u>.- To open the abort boundaries, immediate return was initiated with the main and OMS engines operating at emergency power level. The SRBs were held for their nominal burn time of 100 seconds (including a 3-second tailoff) at which time they were jettisoned. This mode required a change in basic procedure from abort procedures discussed earlier, namely replacing aerodynamic angles with inertial angles during portions of the trajectory. This change was required by two factors. The first was that for a relative velocity of zero, α was undefined, so a change was required to examine "off-the-pad" aborts. The second was that an aerodynamic turn was found to be an ineffective way to turn in this situation. The most effective procedure was to use inertial angles for a complete pitchover (as in an outside loop) so that the thrust was applied in a retrograde mode where the pitch angle (θ_i) was modulated to control the vertical component of thrust and thus maintain a low dynamic pressure. Following completion of the retro maneuver, control was again based on aerodynamic angles allowing direct control of q-α during the remainder of the abort.

The trajectory profile and control histories for the minimum time of failure for a safe abort (off-the-pad) with this procedure are shown in figure 7. The solid lines on the right-hand side of this figure and subsequent ones indicate the active control variables and the dashed lines indicate the resulting time history of the inactive variables. The vehicle was first controlled with inertial angles until SRB burnout, which occurred at the nominal time of 100 seconds. At burnout, the T/W ratio was 0.72 and q was 4500 N/m^2. To increase the T/W and decrease the q, the vehicle flew a lifting trajectory and did not attempt the turnaround for another 92 seconds. At this point, the T/W was 0.85 and q was 0.12 N/m^2. Dynamic pressure never exceeded this value until after turnaround was complete. This general procedure worked for all failures occurring before staging of the SRBs.

The maximum time of failure for safe return, figure 8, occurred 292 seconds into the flight. At that time, turnaround was initiated immediately with a T/W ratio of 1.16 and q of 3 N/m^2. Although not shown, for a failure occurring shortly after SRB staging, the T/W ratio was too low and q was too high for immediate turnaround. For these cases, the vehicle flew a lifting trajectory, as in the cases for minimum safe abort time up to SRB staging, before initiating the pitchover maneuver. The exact crossover point between flying a lifting trajectory and an immediate turnaround was not determined.

AOA - Drop Tank.- This once-around procedure used the maximum available thrust (main engine and OMS) until the external tank was depleted. At this time, the external tank was jettisoned and thrusting continued on the one remaining main engine and OMS until the internal fuel was depleted. As shown in figure 9, the vehicle was lofted to an altitude of 610 km during the abort. In order to enter from this altitude, some α and σ modulation during the entry was required to meet the q-α constraint. The crossrange requirement for this mission was ≈370 km, whereas the crossrange requirement for polar missions would be of the order of 2000 km.

AOA - Hold Tank.- Figure 10 shows the trajectory parameters when the tank was held for the entire thrust period following the failure. This option increased the T/W at the beginning of the internal fuel phase from 1.67 to 3.53, but also decreased the ideal velocity by 183 m/sec. This ideal velocity loss caused a 44-second increase in the minimum time for safe abort. This indicated that reducing the weight of the vehicle while thrusting, even at the expense of T/W, can produce significant improvement in the minimum time.

AOA - Yaw Torquing - Drop Tank.- To reduce the required reentry crossrange, this procedure yawed the vehicle during the powered portion of the abort, figure 11. This changed the heading angle at burnout increasing the inclination of the orbit. For this case, the point of passage over the longitude of ETR was moved northward, reducing the required reentry crossrange. Since the due-East launch required only a low crossrange maneuver for a successful abort, this technique offered no improvement over the drop tank mode. However, for higher inclination orbits, this technique of reducing the crossrange requirement may offer advantages.

Abort Time Gaps.- Figure 12 summarizes the capability of the abort procedures studied to provide a safe return to the launch site after the loss of one main engine. The immediate return category offers safe return for failure occurring between liftoff and 292 seconds into the flight, some 56 percent of the nominal ascent time. With the exception of failure occurring between 22.5 seconds and 75 seconds into the flight (10 percent of nominal), which can be handled by procedures involving no propulsion, or the OMS propulsion only, immediate return aborts must use the remaining main engines. The once-around abort category offers safe aborts for failures occurring between 310 seconds into the flight and insertion (40.5 percent of nominal). Thus, while flying an ascent trajectory optimized for performance and carrying no additional fuel for abort considerations, the unsafe time of failure gap is 18 seconds - 3.5 percent of the nominal ascent time.

CONCLUDING REMARKS

The need for a means of rapidly determining unsafe time of failure gaps for a shuttle ascent trajectory has been satisfied by a recently incorporated extension of the point mass trajectory optimization computer program, POST. Its capability has been demonstrated through application of evaluating abort procedures for an alternate space shuttle concept assuming a instantaneous loss of 25 percent of the main engine thrust while following a performance-designed, due-East, ascent trajectory.

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4. Glass, K. J.; Kirkbride, R. L.; Ellison, J. C.; Spencer, B.; Whitnah, A. M.; and Hillje, E. R.: Aerodynamic Characteristics of a 1.9 Percent Scale Model MSC 040A Space Shuttle Orbiter at Various Reynolds Numbers (M = 0.25). DMS-DR-1215, January 1972.

Table 1

Vehicle Characteristics

Overall System

Orbiter Injected Mass + Payload (29,500 kg)	110,000 kg
Tank Jettisonal Mass (Includes Two Main Engines)	42,000 kg
Solid Rocket Booster Jettisonal Mass	126,000 kg
Orbiter Internal Fuel	16,000 kg
Tank Fuel	725,000 kg
SRB Fuel	807,000 kg

Main Propulsion System

$(I_{sp})_{VAC}$	450.3 sec.
$(\text{Thrust})_{VAC}$	300,000 N
Emergency Power Level (EPL)	327,000 N

Solid Rocket Boosters

$(I_{sp})_{VAC}$	268 sec.
$(\text{Max. Thrust})_{VAC}$	800,000 N

Orbital Maneuvering System

$(I_{sp})_{VAC}$	440 sec.
$(\text{Thrust})_{VAC}$	133,000 N
Throttling Capability	0.2→1.4 nominal

Aerodynamics

Shuttle Designation	$040A_2$
Reference Area (With SRBs and External Tank)	$368 m^2$
Reference Area (With External Tank)	$293 m^2$
Reference Area (Orbiter Alone)	$279 m^2$

ALTERNATE SHUTTLE CONCEPT

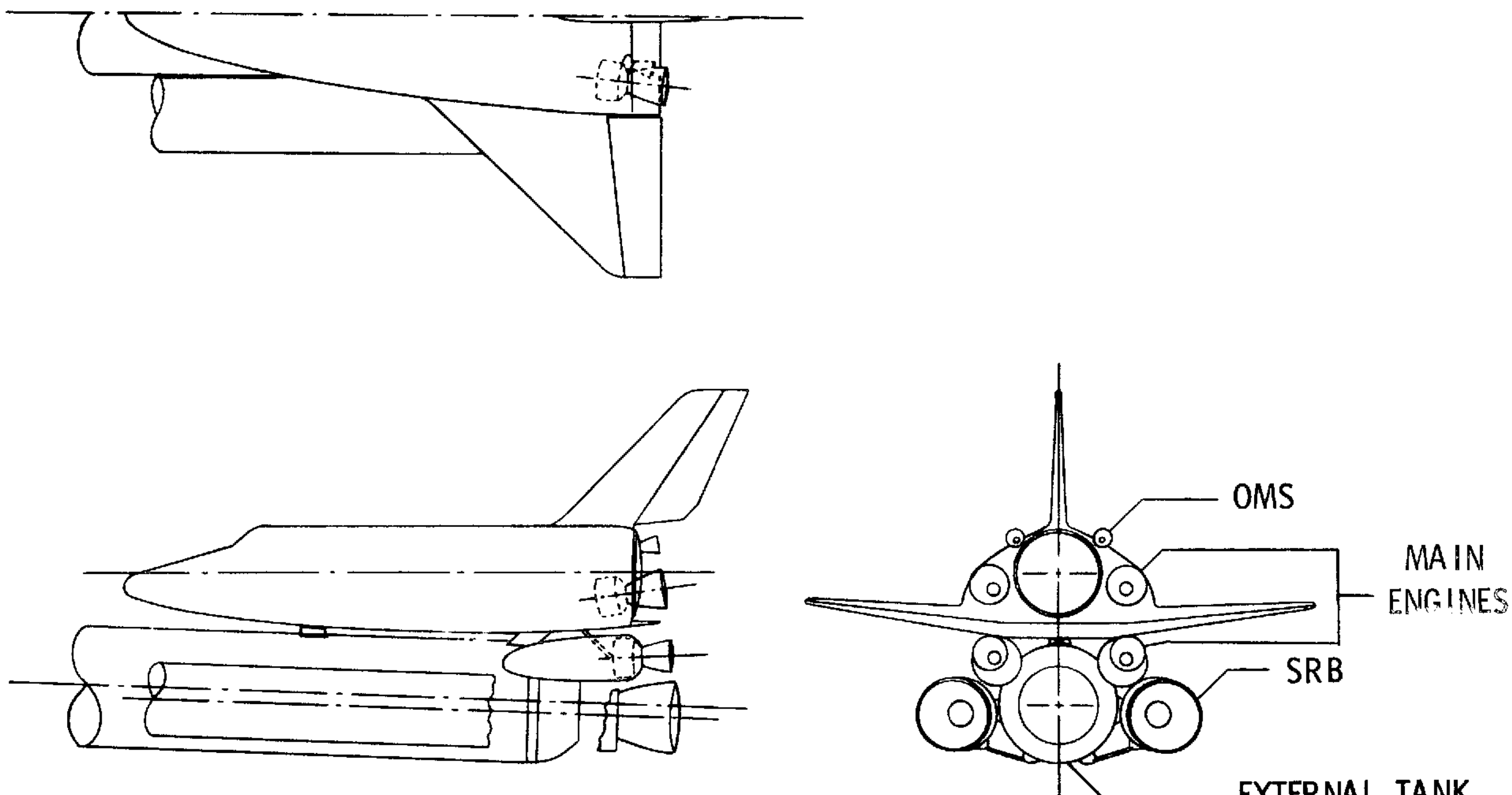

Figure 1

NOMINAL ASCENT TRAJECTORY

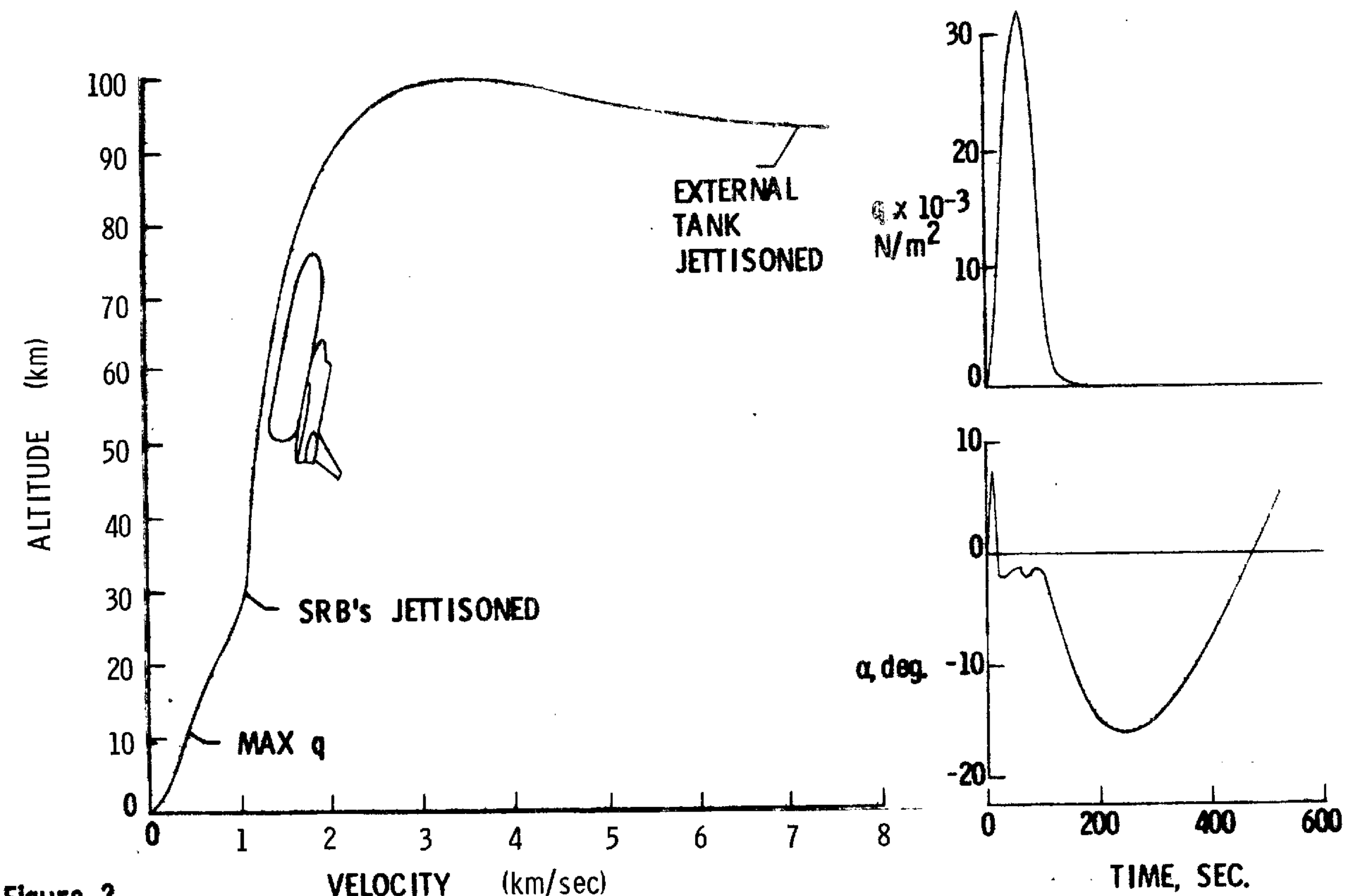

Figure 2

IRTLS - MINIMUM TIME PROCEDURES FOR NO PROPULSION MODE

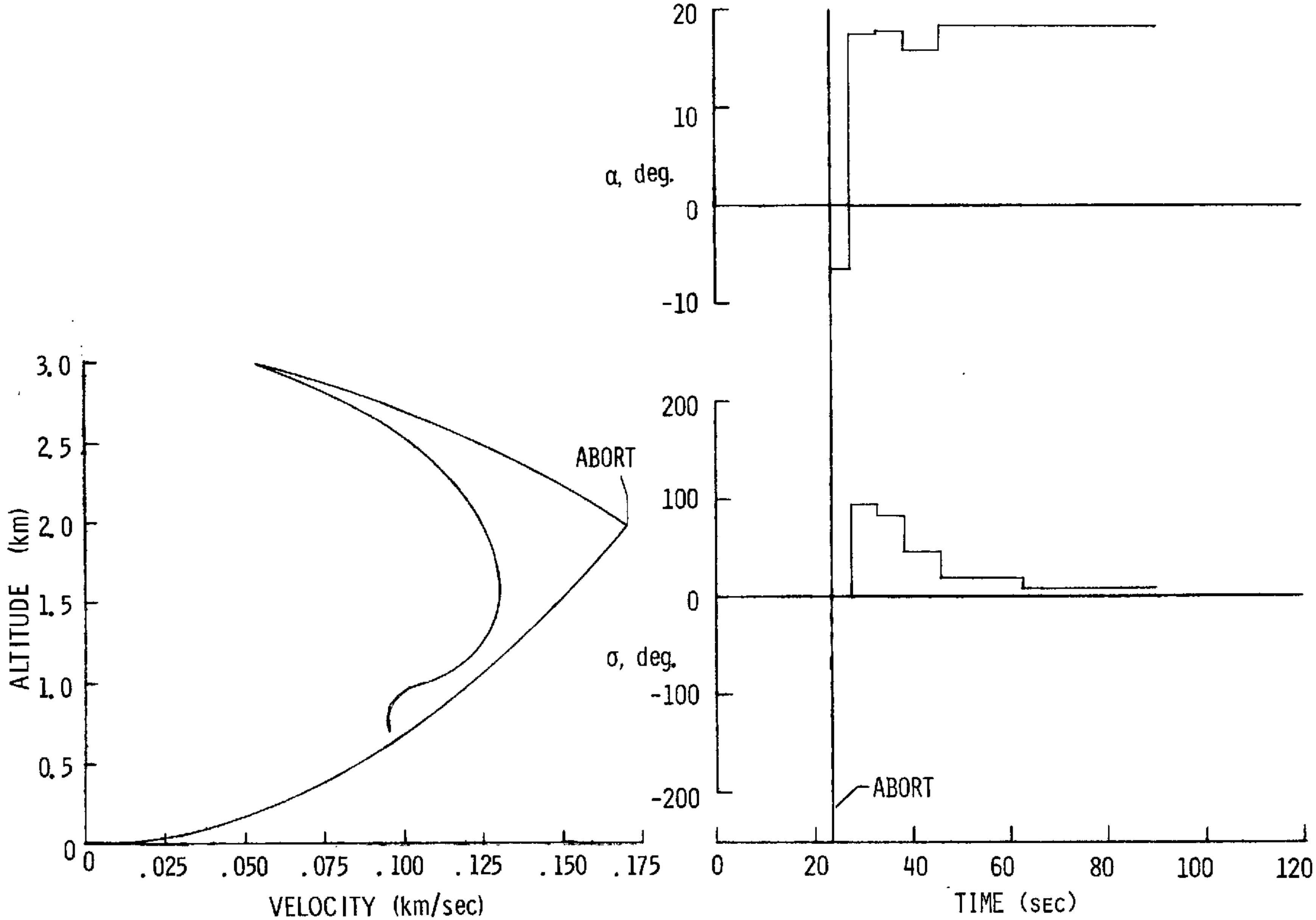

Figure 3

IRTLS - MAXIMUM TIME PROCEDURES FOR NO PROPULSION MODE

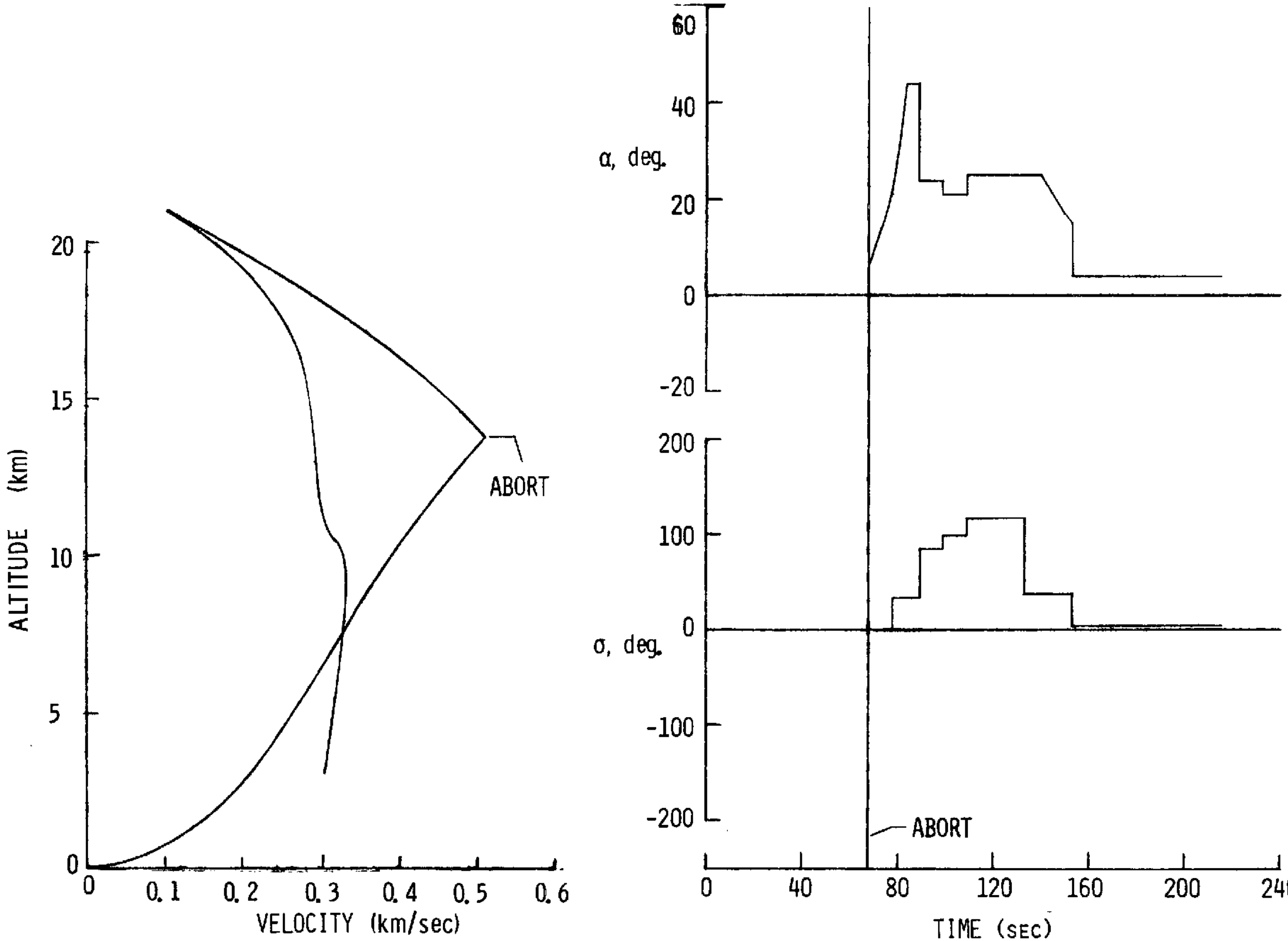

Figure 4

IRTLS - MINIMUM TIME PROCEDURES FOR OMS ONLY MODE

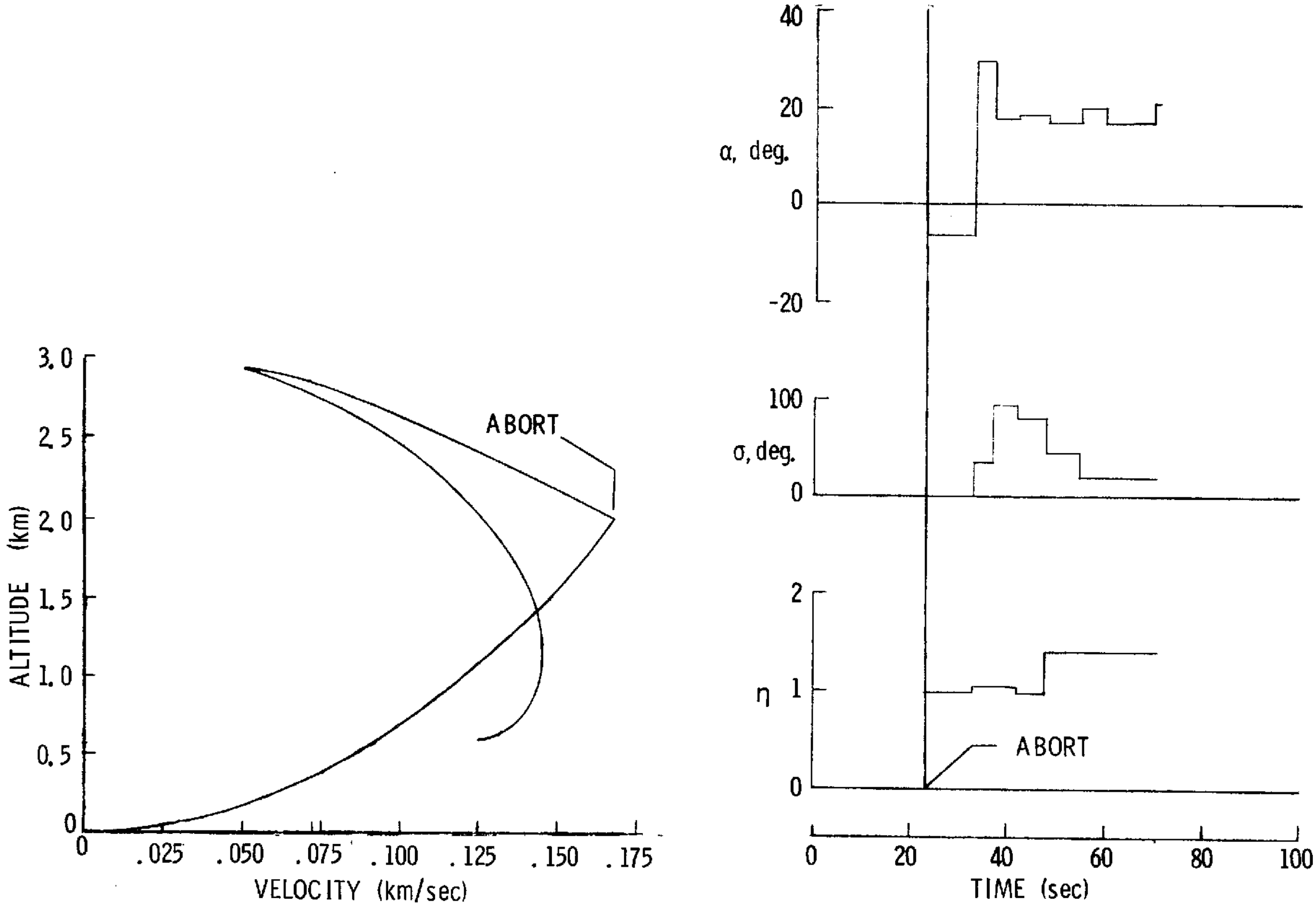

Figure 5

IRTLS - MAXIMUM TIME PROCEDURES FOR OMS ONLY MODE

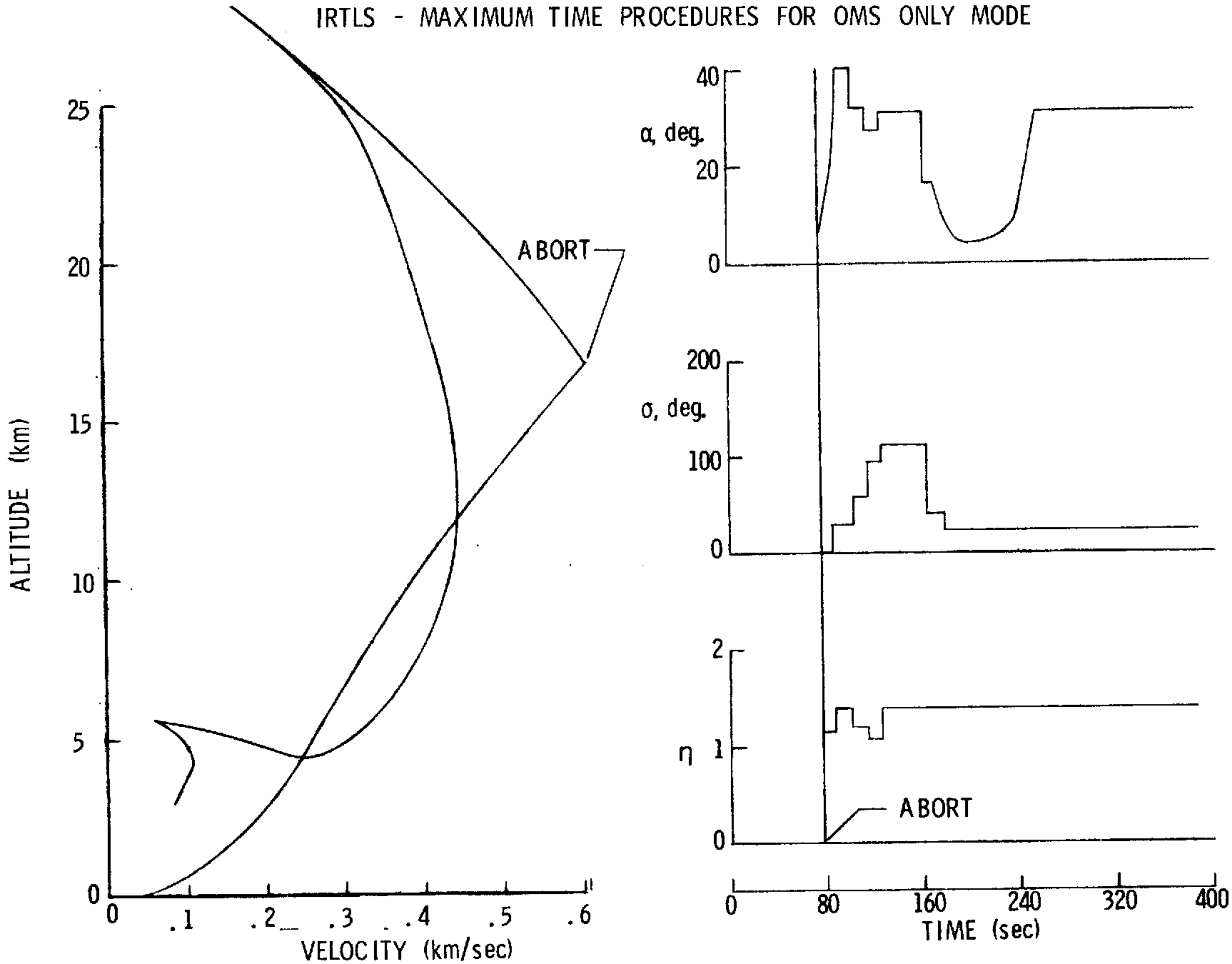

Figure 6

IRTLS - MINIMUM TIME PROCEDURES FOR ALL AVAILABLE PROPULSION MODE

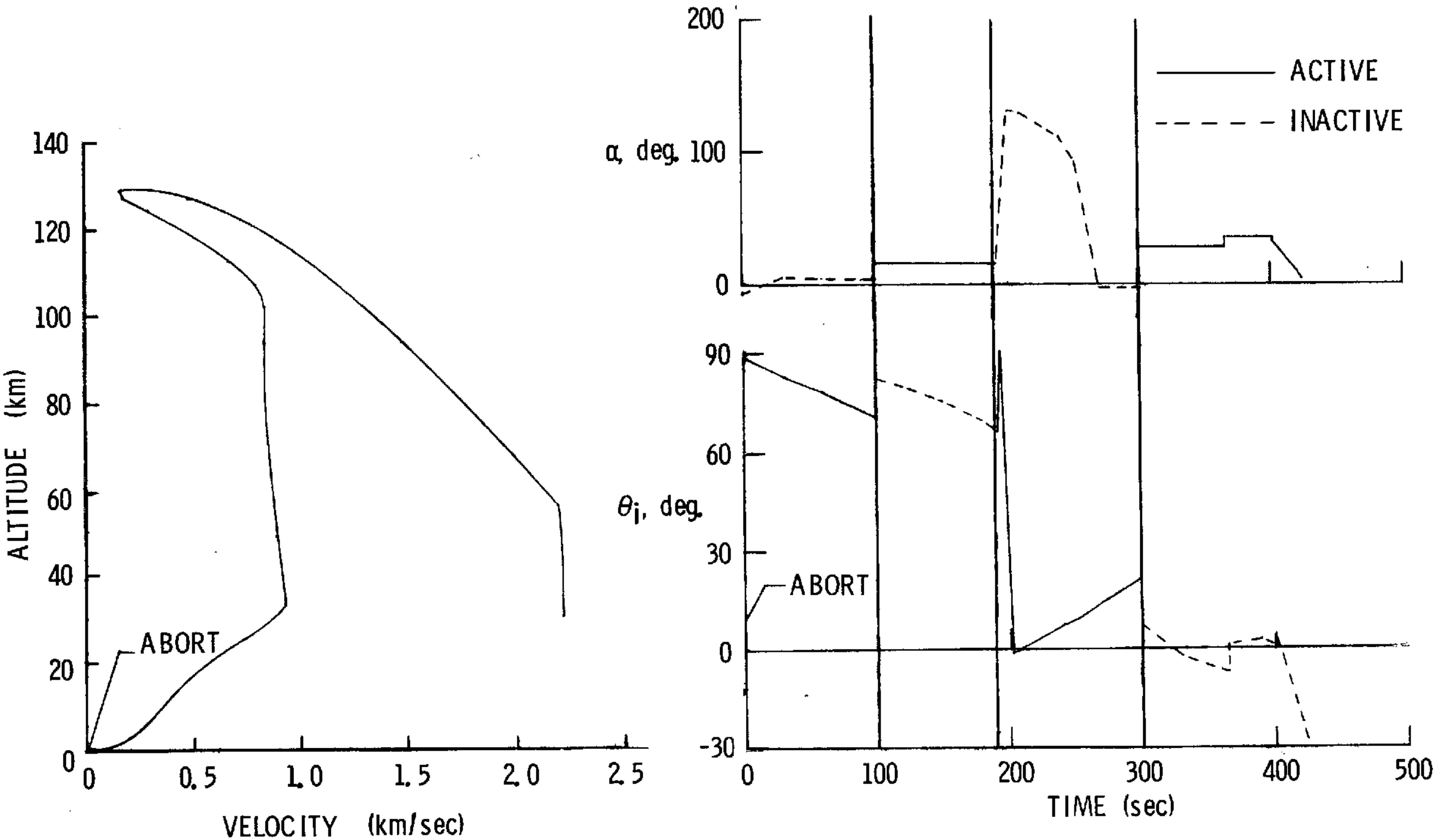

Figure 7

IRTLS - MAXIMUM TIME PROCEDURES FOR ALL AVAILABLE PROPULSION MODE

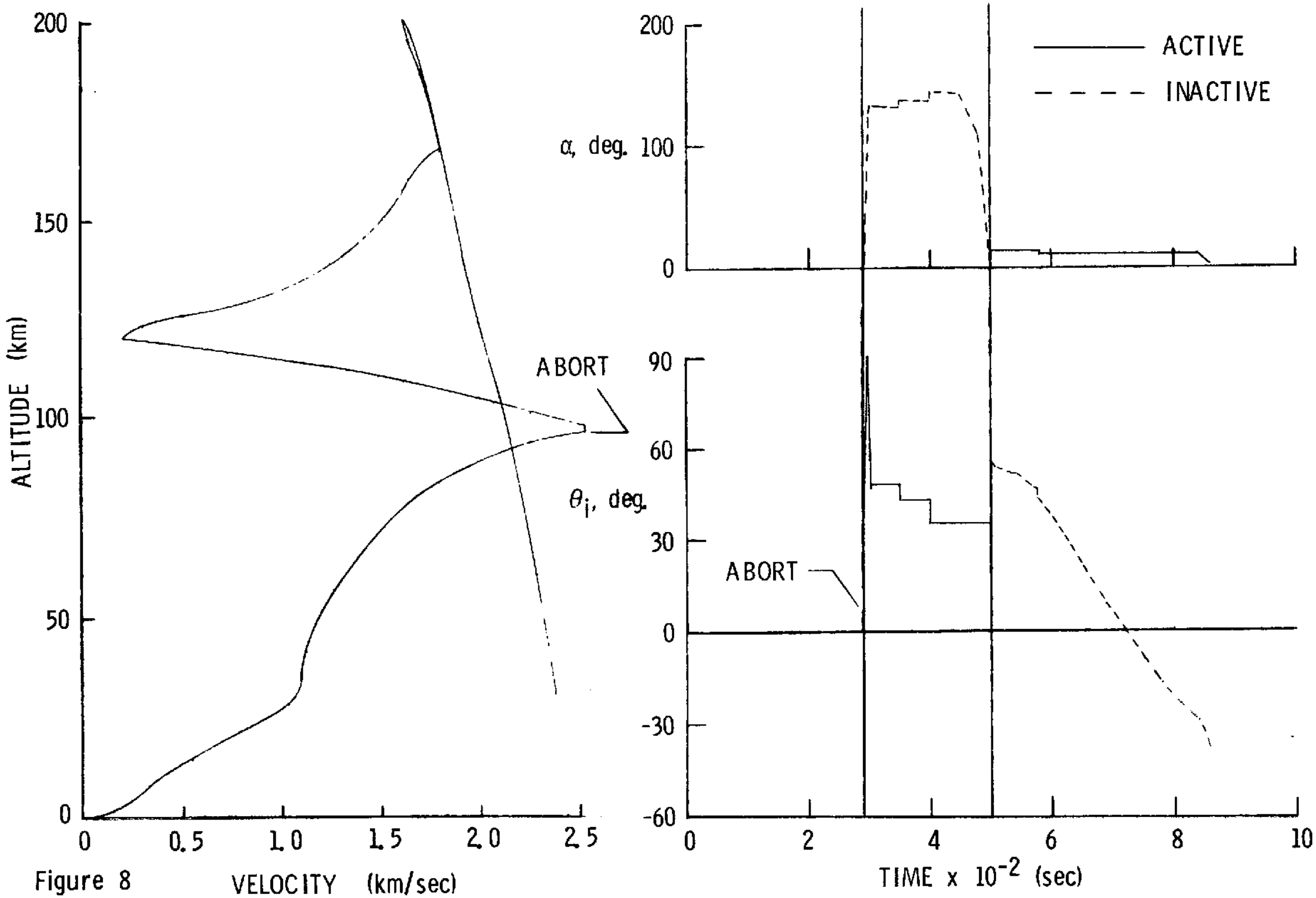

Figure 8

AOA - MINIMUM TIME PROCEDURES FOR DROP TANK MODE

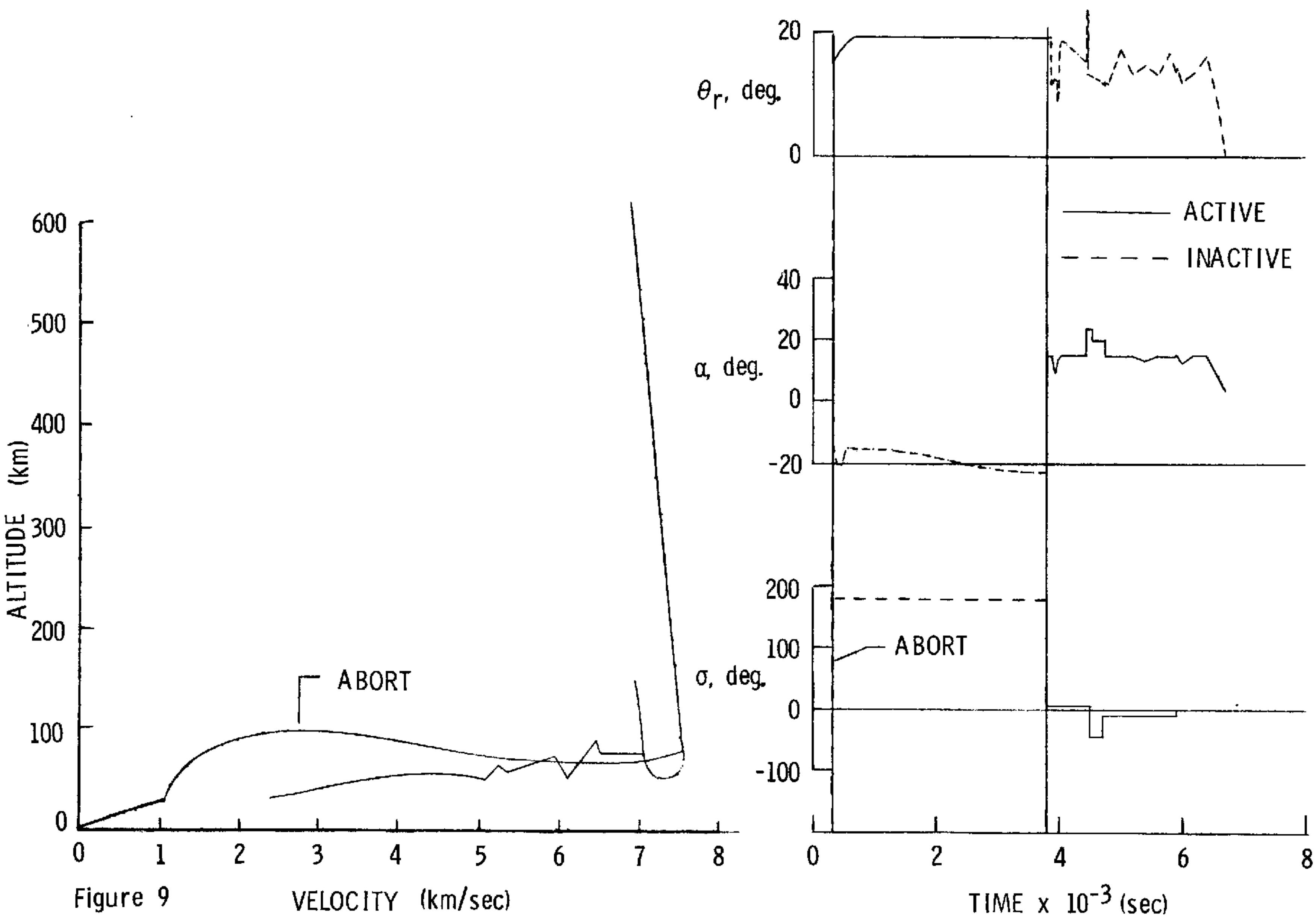

Figure 9

AOA - MINIMUM TIME PROCEDURES FOR HOLD TANK MODE

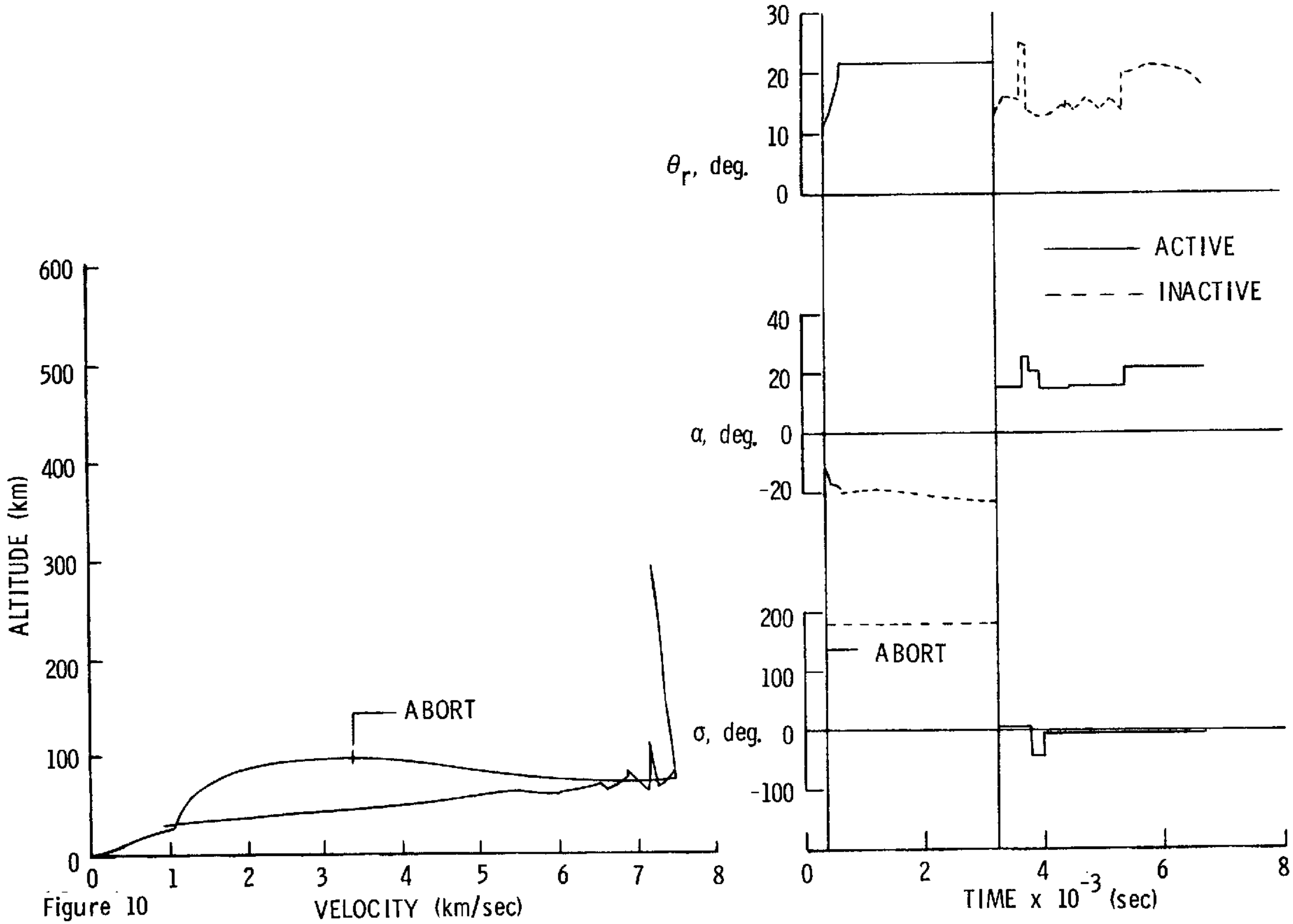

Figure 10

AOA - MINIMUM TIME PROCEDURES FOR YAW TORQUING - DROP TANK MODE

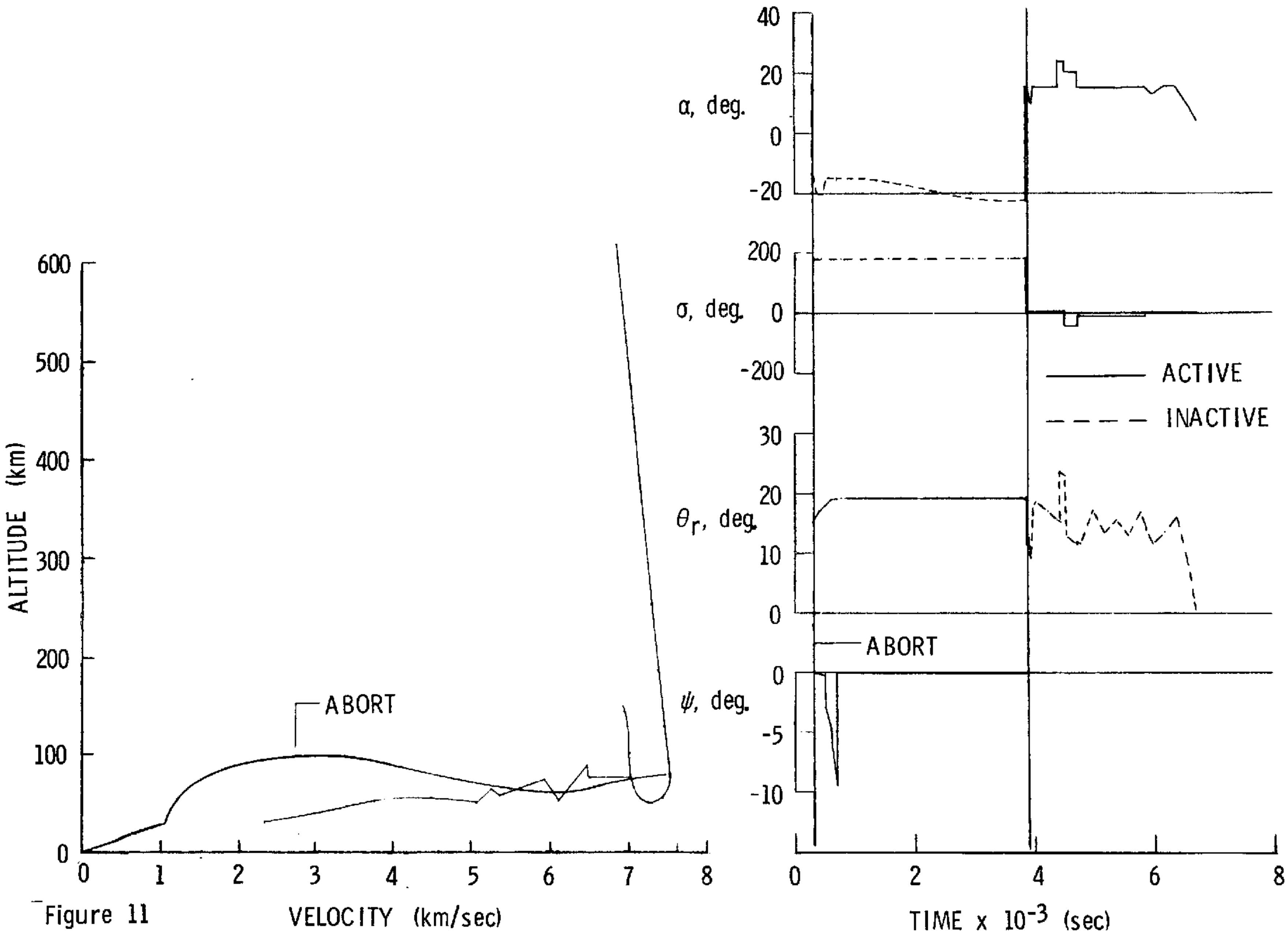

Figure 11

ABORT TECHNIQUE SUMMARY

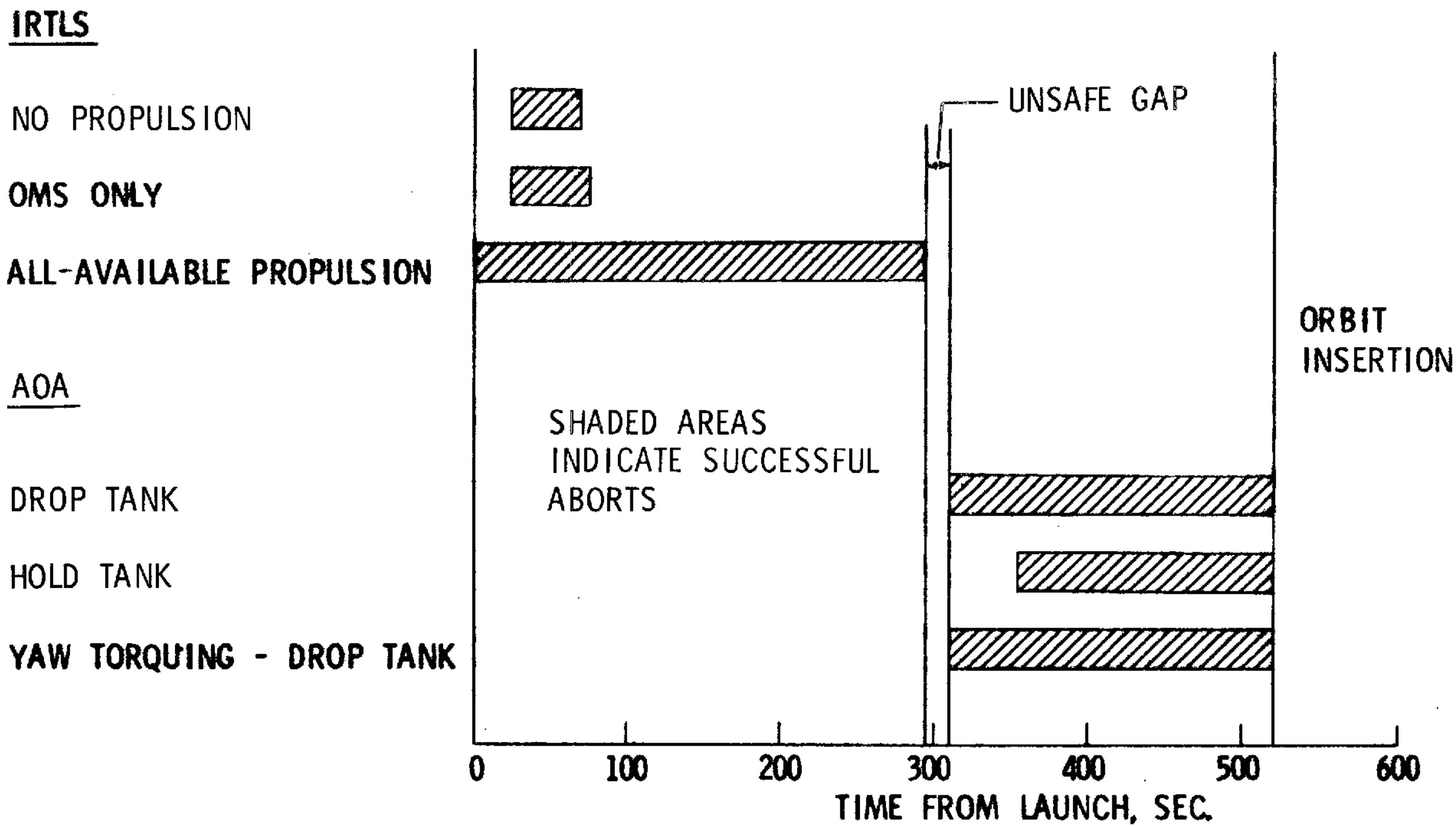

Figure 12